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Development and evaluation on a Wireless Multi-Gas-Sensors System for improving traceability and transparency of table grape cold chain

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ABSTRACT*: There is increasing requirement to improve traceability and transparency of table grapes cold chain. Key traceability indicators include temperature, humidity and gas microenvironments (e.g., CO_2, O_2, and SO_2) based on table grape cold chain management need to be monitored and controlled. This paper presents a Wireless Multi-Gas-Sensors System (WGS^2) as an effective real-time cold chain monitoring system, which consists of three units: (1) the WMN which applies the 433MHz as the radio frequency to increase the transmission performance and forms a wireless sensor network; (2) the WAN which serves as the intermediary to connect the users and the sensor nodes to keep the sensor data without delay by the GPRS remote transmission module; (3) the signal processing unit which contains a embedded software to drive the hardware to normal operation and shelf life prediction for table grapes. Then the study evaluates the WGS^2 in a cold chain scenario and analyses the monitoring data. The results show that the WGS^2 is effective in monitoring quality, and improving transparency and traceability of table grape cold chains. Its deploy ability and efficiency in implantation can enable the establishment of a more efficient, transparent and traceable table grape supply chain.*

Keywords: Table grapes; gas microenvironment monitoring; shelf life prediction; cold chain; traceability and transparency

1. Introduction

The need for traceability and transparency of agro-food chains was driven by numerous recent food safety scandals which triggered growing attentions from governments and consumers. In response, many countries have introduced stricter regulations and smarter industrial development strategies to enable better tracking and tracing of agricultural food products (Aung et al., 2014; Narsimhalu et al, 2015; Gogou et al, 2015; Defraeye et al., 2016). The development of IoT (Internet of Things) and WSN (Wireless Sensor Network) technologies provided more integrated and effective approaches to leverage the huge amount of complex information available nowadays and to enable more effective and easier monitoring of food supply chains (Dehghannya et al., 2010; Pang et al, 2010; Xiao et al, 2016).

Wireless multi-sensors network is a new technology that combines multi-sensors technology and WSN, embedded computing, networking and wireless communication, and distributed processing. It senses and collects information of monitoring objects and sends information to the end-user via wireless and multi-hop network, which has many advantages as low maintenance cost, higher mobility, better flexibility, and fast deployment in special occasions. It is reportedly to benefit quality and safety of products and supply chain optimization and enable quick product recalls of perishable food, which has been adopted in many sectors, such as fruit cold chain (e.g., Ruiz-Garcia et al, 2008; Guo et al, 2011; Xiao et al, 2015; Wang et al, 2015), aquatic products chain (e.g., Qi et al, 2011 & 2014; Ping-Ho et al, 2013; Xiao et al, 2016), winemaking monitoring (e.g., Di Gennaro et al, 2013; Zhang et al, 2015), greenhouse management (e.g., Gnanavel et al, 2016; Jiang et al, 2016), and crops planting (e.g., Garcia-Sanchez et al, 2011; Coates et al, 2013). However, most of these solutions focused on temperature and relative humility. Few previous research described traceability of gas atmosphere, such as ethylene gas (Jedermann et al, 2006).

Given that the cold chain is the key process in the agri-food supply chain to ensure food quality and freshness, key traceability indicators including temperature and other environmental conditions under which the fresh and frozen produces are stored and transported need to be closely monitored and controlled (Bobelyn et al, 2006; Han et al, 2012; Trebar et al, 2015). Unlike other fruits, such as bananas and pears, table grapes deteriorate instead of ripening after harvest. For postharvest decay control and shelf life prolonging, table grapes in the cold chain not only require a temperature-controlled environment, but also some special treatments: for example, fumigated by SO_2 gas or SO_2 generator pads which contain sulfite salt or sodium metabisulphite. As a result, gas atmosphere in the table grape cold chain can be complex: CO_2 and O_2 gases come from the atmosphere and the respiration of table grapes; SO_2 gas slowly released by SO_2 generator pads after reaction with water vapour from humid air.

The increased CO_2 concentration or low O_2 concentration in the cold chain environment will slow down the rate of physiological activity by reducing respiration rate of table grapes, which affects the quality of table grapes significantly (Deng et al, 2005; Costa et al, 2011). SO_2 as exogenous gas will prolong table grape storage by significantly retarding the growth of those pathogenic fungi and preserving the fruit's original flavour and nutrients (Youssef et al, 2015; Carter et al, 2015). Therefore, it is important to monitor SO_2, CO_2 and O_2 gases in the cold chain which significantly affect the quality and safety of table grape. The capability of monitoring SO_2, CO_2 and O_2 gases concentration in real-time will improve shelf-life prediction and the traceability and transparency of the table grape cold chains. Extant literature review suggests that there are no previous studies, which developed effective gas concentration monitoring systems in table grape cold chains. This study, therefore, concentrates on developing a Wireless Multi-Gas-Sensors System (WGS^2) as an effective real-time table grape cold chain monitoring system.

This paper is organized as follows: Section 2 presents system analysis and architecture design of WGS^2. Multi-gas-sensors development and signal processing for table grape cold chain are demonstrated in Section 3. Section 4 details the WGS^2 system testing and evaluation in a real cold chain logistics. This paper concludes with the discussions and suggestions for future research.

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2. WGS^2 System Analysis and Architecture Design

2.1 cold chain example and field study method

In this research, two sample table grape cold chains are discussed to illustrate a long distance chain and a short distance chain in China (see Fig.1). One sample table grape cold chain is from Xinjiang province to Guangdong province in China. Another sample table grape cold chain is from Hebei Province to Tianjin city in the North China.

Fig.1 The mapping for table grape cold chain

A systematic literature review, a field observation and interview were conducted to extract the monitoring requirements of the WGS^2 and the factors that may influence the safety & quality of table grape cold chain. The interviews were conducted face-to-face with 5 cold chain managers and 20 infield cold chain workers from both example cold chains over 7 days. All of the interviewees have over 3 years of working experience in the table grape cold chains. Each interview lasted for around 40 minutes. Interviewees were asked about *their working routine; whether they record gas information; how they estimate the shelf life of table grapes; whether they knew about wireless gas monitoring and if so whether they have used it before; and what kind of information they think are supply chain traceability information.*

2.2 Business flow analysis and traceability information requirements of the WGS^2

The field study also helped to clarify the business flow of the table grape cold chain. The business flow of a typical ‘seedless grape’ cold chain is shown in Fig. 2. The cold chain process starts from the farm and ends with on-the-shelf retail with the following stages:

- Step 1: Grape harvesting. Usually the harvesting happens during a non-rainy cooler times of the day (<25℃) (usually early morning) to prolong the cooling time of the table grapes.
- Step 2: Ordinary/Refrigerated transportation. Table grapes are transported immediately via ordinary or refrigerated transport to the refrigeration warehouse for further processing. During this process, table grapes are surrounded by normal CO_2 and O_2 gas in the atmosphere. Some of the table grapes are directly transported to nearby markets for display and sale.

- Step 3 & 4: Table grape precooling and cold storage. In the warehouse, table grapes will firstly be packed in sealed packages fitted with SO_2 generator pad or powder, which reacts with water vapour from the humid environment and produce a continuous emission of low SO_2 concentrations within the packages. Then table grapes are precooled for 12-24 hours at -1~0℃. Finally, table grapes are kept in cold storage until further transportation to the market for display and sale.
- Step 5: Transporting the table grapes to the market or wholesale store. In this process, table grapes are transported using refrigerated trucks. During this process temperature and the gas fluctuations, such as SO_2, CO_2 or O_2, may cause safety and quality problems issues such as brown stain, botrytis cinerea during the cold chain logistics process.
- Step 6: Temporary storage for display and sale. The grapes are temporarily stored for display and sale by wholesalers or retailers.

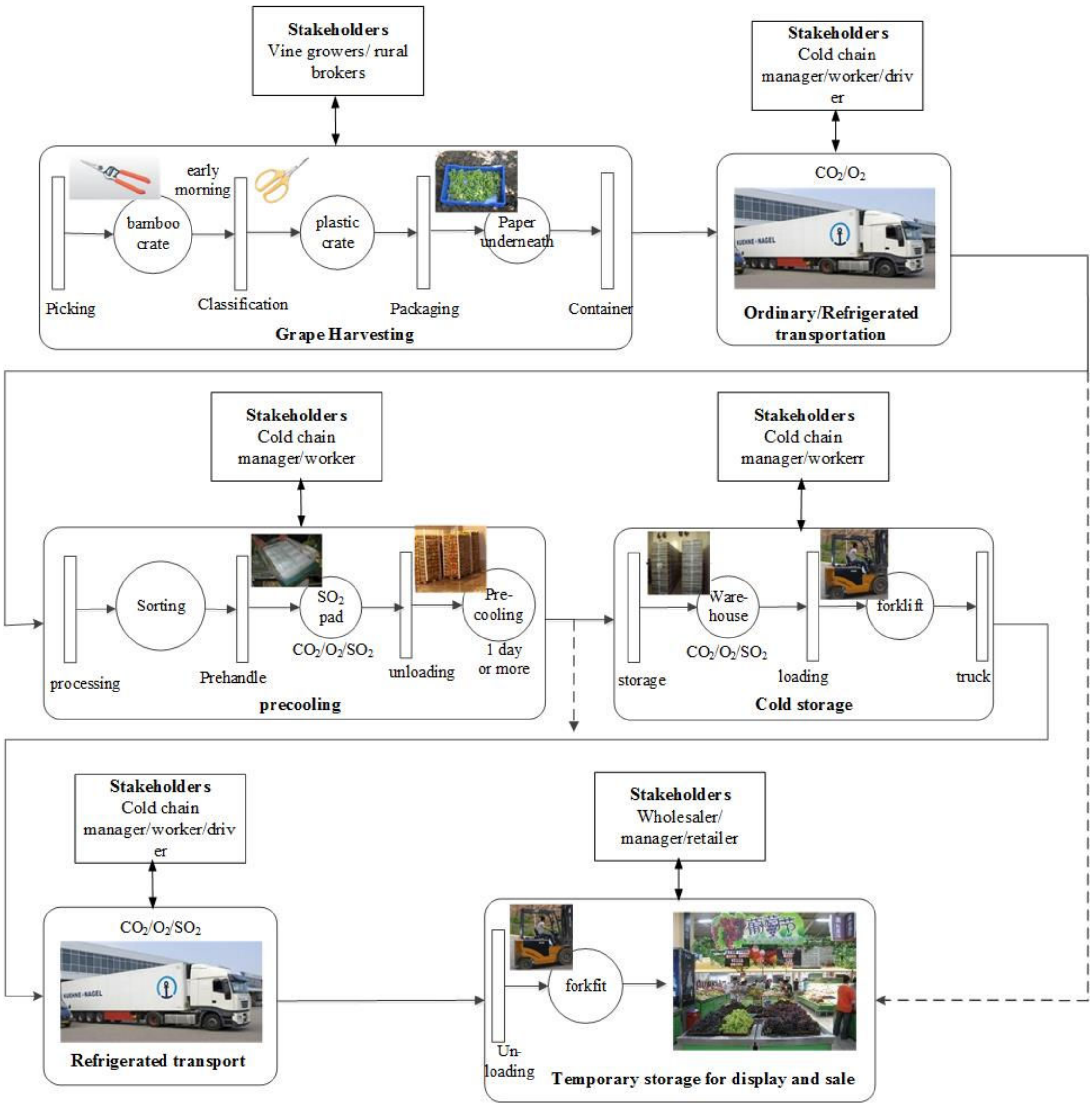

Fig. 2 Process and information flow of table grape cold chain

Multiple steps are involved in table grape cold chain from the farm to display. Changes in temperature, relative humidity and gaseous at any stage can greatly affect the quality of the fruit.

Therefore, it is essential to extract the traceability information from the table grape cold chain. Based on the interview responses and the extant literature review (Zhang et al, 2010; Palou et al, 2010; Ustun et al, 2012; Champa et al, 2015; Thakur et al, 2015; Koutsimanis et al, 2015; Zubeldia et al, 2016), key traceability indicators and quality indicators are identified. Table 1. lists traceability information and requirement of the WGS^2. The critical traceability indicators including the temperature, the relative humidity, volume fractions of SO_2 gas, CO_2 gas and O_2 gas in a fixed time. Moreover, other key quality indicators mainly included SSC (Soluble Solids Content), pH values, brown stain, and shelf life. The WGS^2 are required to be able to acquire real-time information on temperature, relative humidity, O_2, CO_2, SO_2 in the cold chain in a remote centre, to be able to predict the shelf life of the table grapes, to be user-friendly in operation for quality assurance, and to be implemented at low cost.

Table 1. Traceability information and requirement of the WGS^2

Steps of cold chain	Key actions	Key environment indicators	Preferred Level Criteria	Stakeholders	Main user	Key quality indicator
Harvesting	Reduce grape ripeness, cooling, no dew, pack only one layer in box	T, RH	T<25℃	Vine growers/rural brokers	Vine growers	Sugar level (sweetness), acid level (acidity taste)
Ordinary/ Refrigerated transportation	Fast transportation, less vibration	T, RH, O_2, CO_2	-	Cold chain manager/worker/driver	driver	SSC, PH level, brown stain
Precooling	Fast cooled within 12-24 hours, filled with SO_2	T, RH, O_2, CO_2,SO_2	T: -1～0℃ RH: 90-95%	Cold chain manager/worker	Cold chain worker	SSC, PH level, brown stain
Cold storage	Ventilation, low temperature, high humidity	T, RH, O_2, CO_2, SO_2	T: -1～0℃ RH: 90-95%	Cold chain manager/worker	Cold chain worker	SSC, PH level, brown stain, shelf life
Refrigerated transportation	Fast transportation, less vibration, low temperature	T, RH, O_2, CO_2, SO_2	T: -1～0℃ RH: 90-95%	Cold chain manager/worker/driver	driver	SSC, PH level, brown stain, shelf life
Temporary storage for display and sale	Cooled storage, handled carefully	T, RH, O_2, CO_2, SO_2	T: -1～0℃ RH: 85-95%	Wholesaler/manager/retailer	Shop manager/staff	SSC, PH level, brown stain, shelf life

Notes: T-temperature, RH-relative humidity

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2.3 System Architecture Design of WGS^2

Based on the traceability information requirements identified from the field observation and the field survey, the WGS^2 structure was developed, which consists of three basic units (see Fig.3): a) the WMN (Wireless multi-sensors network); b) the WAN (Wide Area Network); and c) the signal processing unit:

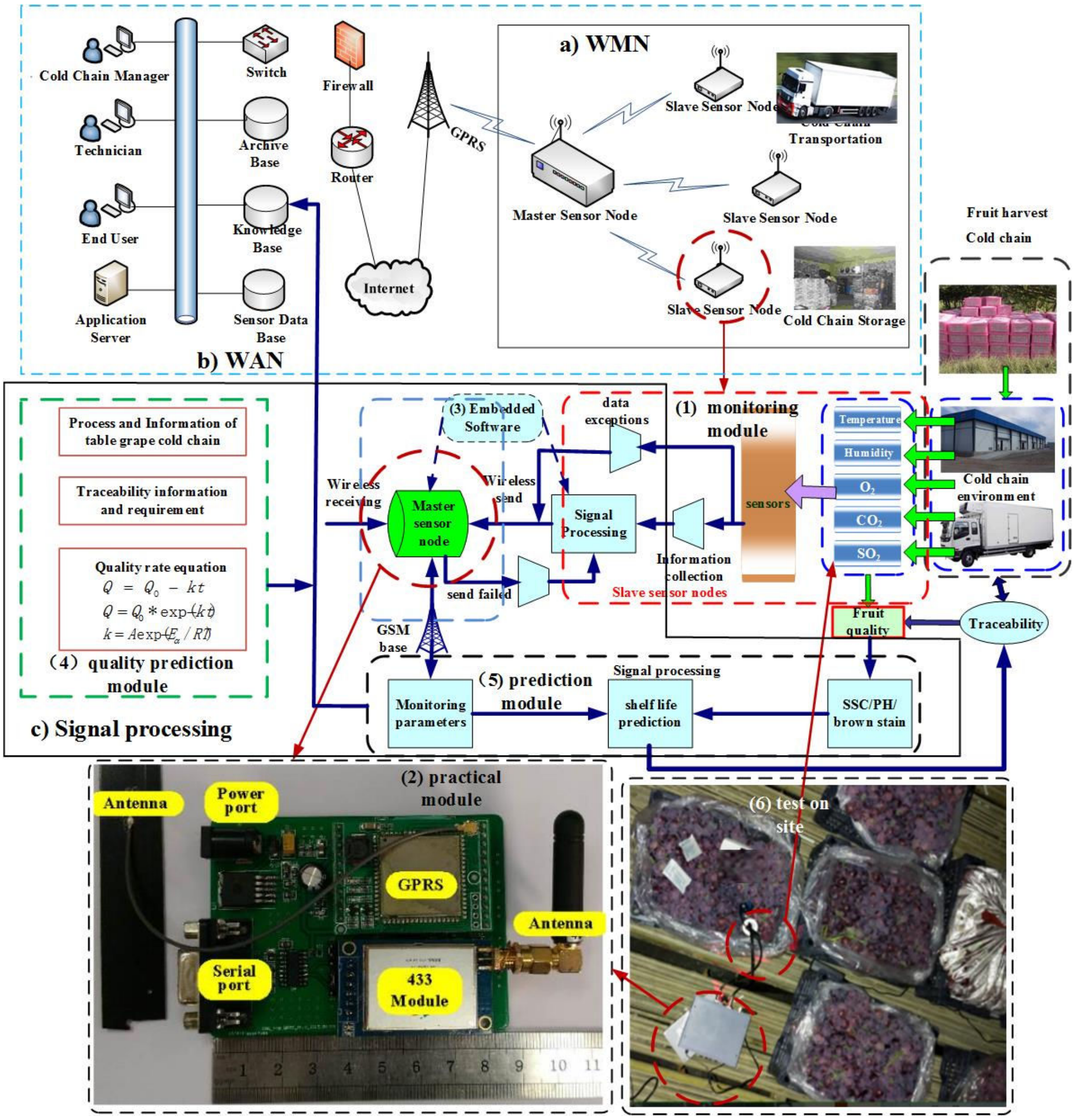

Fig. 3. The system architecture of WGS^2.

- The WMN, which combines multi-sensors technology and wireless sensor network technology, is responsible for collecting and transmitting the data in real-time. It consists of a number of SSNs (Slave Sensor Nodes), or optional router nodes and a Master Sensor Node (MSN). The SSN was used as the real-time remote monitoring terminal to monitor the temperature, relative humidity, SO_2, CO_2 and O_2 levels in a periodical mode as shown in (1) monitoring module in Fig.3, while the MSN (see (2) practical module in Fig.3) not only creates and controls the entire network, but also aggregates the sensor data from the sensor nodes. Previous study showed that wave propagation inside a closed container is significantly higher at 433 MHz than at 915 MHz or 2.4 GHz (Ferrer, 2010). Hence, the radio frequency of the WMN unit is set at 433MHz to increase the transmission performance during the wireless communication between the SSN and the MSN, which is implemented directly or via the router node as a relay. The WMN is installed in the container of the vehicle or refrigeration warehouse.

- The WAN serves as the intermediary to connect the users and the sensor nodes to keep the sensor data without delay through the GPRS remote transmission module. It provides a widely accessible interface for the end users to easily obtain the real-time information about the cold chain via Internet and identify any problems that may lead to decay of grapes.
- Signal processing unit contains an embedded software (see (3) embedded software in Fig. 3) and the shelf life prediction for table grapes. It carries out signal processing of shelf life prediction as shown in (5) prediction module in Fig. 3 based on the quality rate equation as shown in (4) quality prediction module in Fig. 3 as well as signal processing of software embedded in the system of WGS^2 which is used to drive the normal operation of the system hardware. The quality rate equation as shown in (4) quality prediction module in Fig. 3 contains zero-order reaction kinetics model, the first-order reaction kinetics model and Arrhenius equation.

3. Multi-Gas-Sensors development and signal processing for table grape cold chain

3.1 Multi-gas-sensors specification and integration

Based on the field study and the extant literature review, sensor requirements are specified in Table 2. Since the gases composition in the cold chain are very complex and dynamic due to the mixture of SO_2 gas, CO_2 and O_2, the gas sensors were tested and specified during the cold chain monitoring process. Literature shows that there are many gas sensors available in the market, but not all of them can satisfy the monitoring requirement of table grape cold chain (Aiello et al, 2012; Wang et al, 2016; Xiao et al, 2013; Xiao et al, 2015). Therefore, it is necessary to develop multi-gas-sensors to improve the traceability and transparency of table grape cold chain. The theoretical range of gas sensors are not common to develop in actual market, which need to be customized and calibrated. This is especially important for the SO_2 sensor, since volume of SO_2 is only 0-20 ppm in the table grapes cold chain, which is very small in range compared to the SO_2 volume in the industry. For this reason, the sensor resolution was required to be 1 ppm and the sensor range was required to be 0-150ppm, which improve the accuracy of monitoring data for table grape chain.

Table 2. Monitoring parameters for table grapes cold-chains

Parameter	Temperature range	Humidity range	Volume of O_2	Volume of CO_2	Volume of SO_2
Theoretical range	-2℃-36℃	50%-95%	1%-21%	0%-15%	0-20 ppm
Sensor module	AM2322	AM2322	AP-M	ATI	MF-20
Sensor range	-40℃-80℃	0%-99.9%	0%-30%	0%-15%	0-150 ppm
Sensor accuracy	<±0.3℃	±2% RH	±2% FS	±2% FS	±1 ppm
Response time	5s	5s	<15s	<30s	<30s
power Consumption	<0.1 mW	<0.1 mW	<100 mW	<25 mW	<100 mW

The multi-gas-sensors are integrated into the SSN as shown in Fig. 4. Both the SSN and the MSN apply the radio frequency of 433MHz to increase the transmission distance, which form a wireless sensor network. A GPRS module in the MSN is used to communicate between the MSN in the vehicle and the remote server via the RS232 bus.

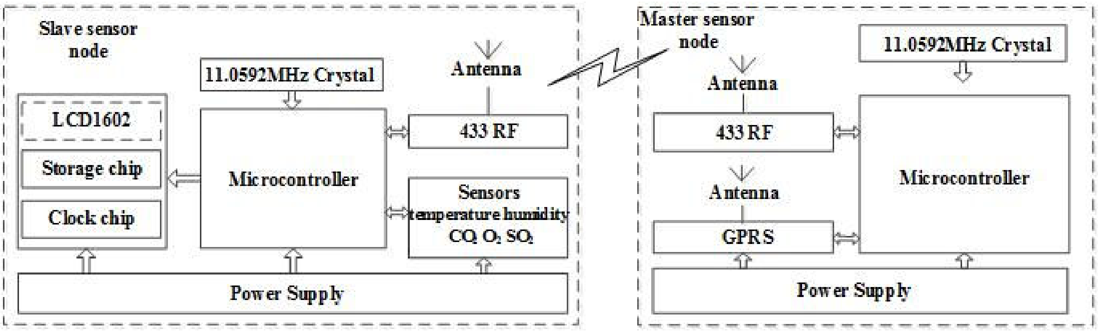

Fig. 4. Block diagram of the SSN and WSN hardware

The development environment and the design of the prototype and the PCB board followed Altium Designer (2004):

- In order to improve processing speed and improve the capacity of disturbance resistance, the STC12LE5A60S2 is used as the microcontroller to realize system functionality of the SSN and the MSN. It has four 16-bit timers, two full duplex asynchronous serial ports and an advanced instruction set architecture.

- Storage chip is used to save sensor information when signals are cut off in long international transport. Clock chip is used to control the time when data collected will be saved and produce timing pulse to wake up the CPU. LCD1602 is optional, but it can be used to display information when the sensor nodes are tested.

- Multiple sensors are used to measure levels of the temperature, the humidity, the volume of SO_2, CO_2 and O_2 gases. The output type of temperature and humidity is digital signal, and the output type of gas sensors is voltage which is measured using an ADC on the microprocessor in cycled time.

3.2 Multi-gas-sensors calibration

The sensors' specification (e.g. point zero) can be adjusted to be consistent with the calibration source when the sensors' specification deviates from the calibration source. The calibration criteria follow the principle of minimizing the square error in the concentration (Feng et al, 2010; Romanak et al, 2010; Medina-Rodríguez, 2015). In order to measure gas concentration, the gas sensors also need the function to respond to different values of the concentration. In our calibration experiment, the sensor response is measured by SO_2 of 0, 19.6, 50.2 and 98.3 ppm, where the SO_2 is produced by a gas automatic control device manufactured by China Agriculture University. Fig. 5 shows how the response (in voltage) of the sensor increases with the increase of SO_2, which is proportional to its voltage signal. The regression of the relationship between voltage signal and SO_2 concentration is given in equation (4), where the coefficient of determination R^2 is 0.9958. Hence, for any given level of SO_2 concentration, the voltage signal corresponds to a certain concentration level. The regression of the relationships between voltage signal and CO_2

and O_2 concentrations are given in equations (5) and (6), respectively.

$$y = 60.39x - 23.87 \tag{4}$$

where x is the voltage signal (V) and y is the volume fraction of SO_2 (ppm).

$$y = 9.36\%x - 3.84\% \tag{5}$$

where x is the voltage signal (V) and y is the volume fraction of CO_2 (%).

$$y = 18.75\%x - 7.5\% \tag{6}$$

where x is the voltage signal (V) and y is the volume fraction of O_2 (%).

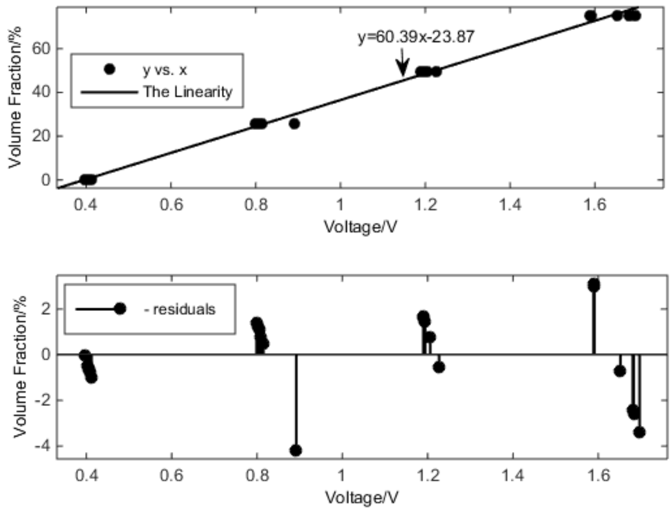

Fig. 5. Linear Regression of SO_2 Sensors' Response

3.3 Multi-Gas sensing signal processing

Multi-Gas sensing signal processing includes two parts: signal processing of software embedded in the WGS[2] system and shelf life prediction. The signal processing of embedded software is responsible for sensor data acquisition and driving the hardware to normal operation. Shelf life prediction is to count the length of time grapes can be stored before becoming unsuitable for consumption. The shelf life prediction model was based on the theory of zero or first-order reaction kinetics model and the Arrhenius equation (Chen et al, 2016). The quality monitoring indexes include SSC, pH values, and brown stain levels, which are indicators of postharvest ripening for table grapes (Villa-Rojas et al, 2011). The situations with different concentrations of SO_2 was considered when modelling the evolution of SSC, pH values and brown stain levels, respectively.

Following steps are shown in the flow chart (see Fig. 6.):

Step 1: Initialization of the SSN and the MSN, such as the initialization of the clock, EEPROM (Electrically Erasable Programmable Read-Only Memory), UART (Universal Asynchronous Receiver/Transmitter) interrupt and the network.

Step 2: The MSN starts a network and waits for the network joining requests from the SSN. Then the system starts the timeout event through checking whether time is counted.

Step 3: Then the interrupt event occurs when slave sensor node first starts collecting the sensor data of temperature, humidity, CO_2, SO_2 and O_2 gas.

Step 4: After the sensor data collection, the system starts to check if EEPROM stores the sensor data and prepares to save the sensor data and time.

Step 5: After that, the system requests function which belongs to the 433 module of the SSN to send the data. Then the MSN starts receiving the data and storing them into a buffer array, and then waits for the UART transmission to carry out transmission to the remote control terminal via the GPRS module.

Step 6: The sensor node will sleep until the next timeout event after the successful data transmission. If it fails to send the data, the system will retransmit the sensor data.

Step 7: The system will predict the shelf life of table grape according the model which developed and evolved by reaction kinetics model and the Arrhenius equation.

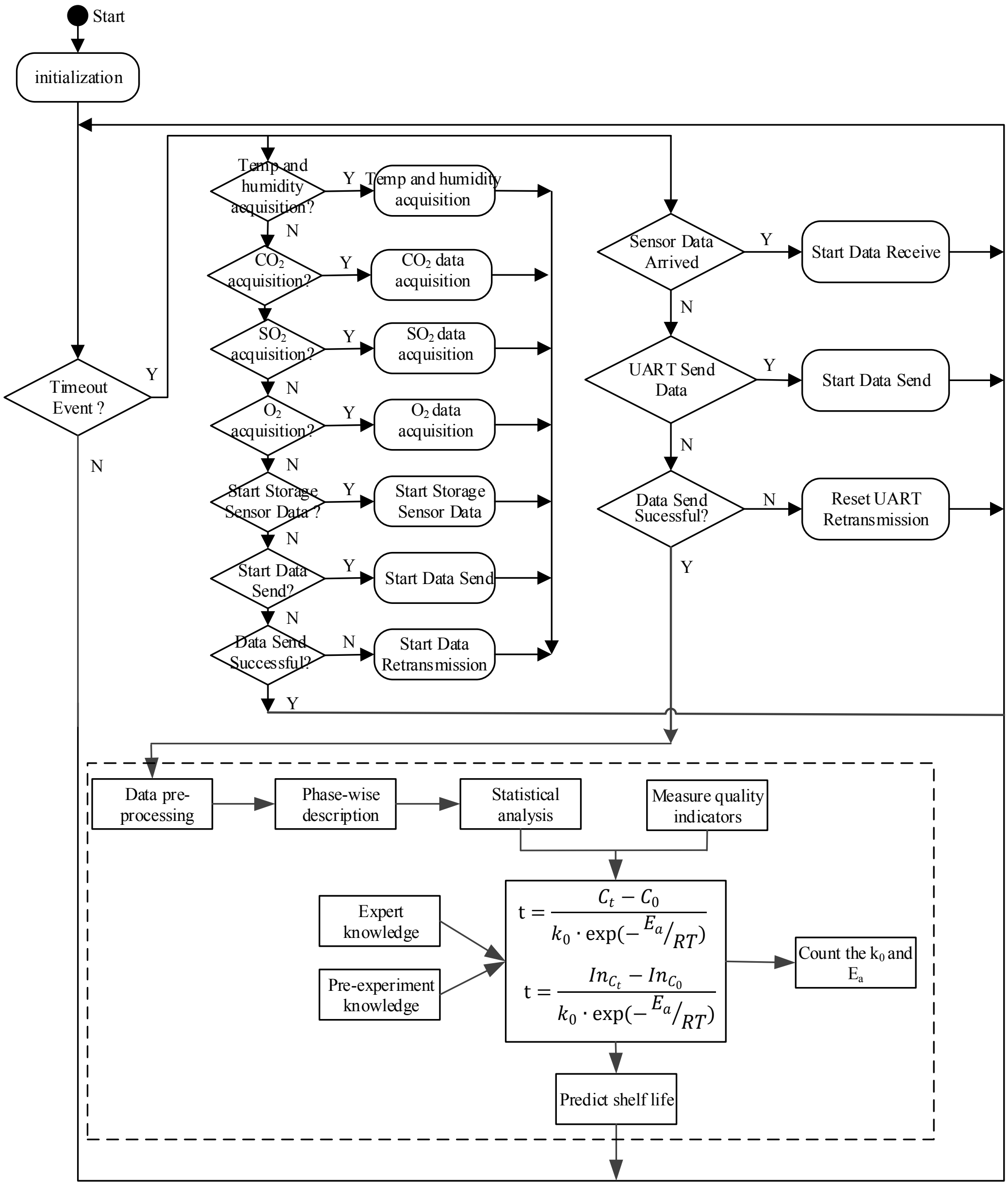

Fig. 6. Flow chart of multi-gas sensing signal processing

4. WGS^2 Testing and Evaluation

4.1 Experiment scenario and design

The WGS^2 system was implemented and tested in two table grape chains from Hebei to Tianjin and from Xinjiang to Guangdong. There were 10 tons of Kyoho grape were transported in a refrigerated truck from Hebei to Tianjin, China, and 10 tons of seedless grape were transport in a refrigerated truck from Xinjiang to Guangdong, China. The length, width and height of the refrigerated container are 12.032m×2.352m×2.385m. A MSN and 10 SSNs were installed in both trucks. Fig.1 indicates the nodes deployment in the refrigerated truck during transportation. The MSN was installed in the driver's cabin and the data-receiving terminal was installed in a remote control centre.

The data sample interval of the sensor nodes was set to 1 second, and the data sending interval of the MSN was set to 1 minute. The length of data sending was 19 Bytes, which included the SSN ID (1 Byte), the temperature data (3 Byte), the humidity data (3 Byte), the SO_2 gas data (4 Byte), the CO_2 data (4 Byte) and the O_2 gas data (4 Byte). The MSN aggregates the data acquired from the 10 SSN with every sample interval (1 s) and transmits the sampled data to the WAN layer, and then send the quality prediction via the GPRS module for every data-sending interval (1 min).

Four experiments were conducted for analyzing the performance of the WGS^2 system:

- The first experiment aimed to analyze the monitoring data of WGS^2 in the table grape cold chain according to the implementation scenario.
- The second experiment was to build shelf-life prediction model which link the quality indicators to the temperature and SO_2 level.
- The third experiment was to check the battery status of each sensor node.
- The last experiment was a system evaluation of the WGS^2 for improving the temperature and gas transparency of the cold chain.

4.2 Monitoring data analysis of WGS^2 in the table grape cold chain

4.2.1 Table grape chain from Hebei to Tianjin

The plot of the temperature and relative humidity in the table grape cold chain from Hebei to Tianjin is shown in Fig 7.

- The AB segment is the table grape harvesting process at the farm, where the temperature and relative humidity vary with the ambient temperature and relative humidity. The average temperature is 22.77℃ and average relative humidity is 54.83% in this process.
- The BC segment is the ordinary transportation process from the farm to cold storage by the ordinary truck.

- The CD segment is the pre-cooling process, where the temperature is about −2℃ in the cold storage after the ordinary transportation.
- The DE segment is the cold storage process to wait for wholesalers to purchase, during which the temperature is stable at about 0℃. The E point is when table grapes are loaded onto thetruck, and the ambient temperature in this process rises to about 16℃.
- The EF segment is the refrigerated transportation process. The F point is when table grapes are unloaded from the truck, and the temperature in this process is about 14℃.
- The temperature then reduces to about 8 ℃ rapidly, before the table grapes are packed in the refrigerated storage, when the temperature decreases rapidly from the normal temperature to the refrigerated temperature at about −1℃ in the FG segment, which stands by temporary storage for display and sale. The results show that WGS^2 system worked well and reflects the temperature and humidity information of table grape cold chain logistics.

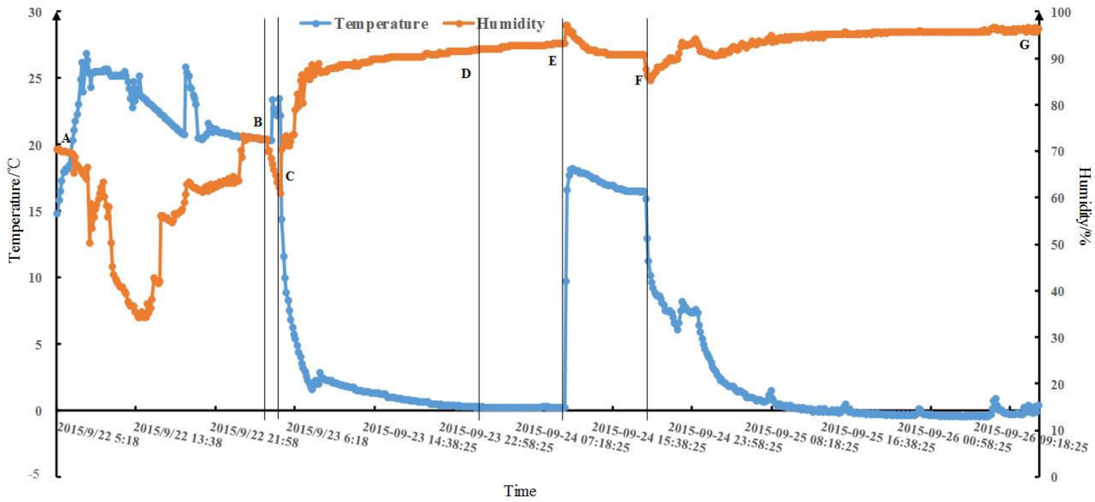

Fig. 7. The plot of the temperature and relative humidity in the table grape cold chain

The plot of the volume fraction of SO_2 and CO_2 in the table grapes cold chain from Hebei to Tianjin is demonstrated in Fig. 8. Before the SO_2 generator pads are placed in table grape packages, the volume fraction of SO_2 is 0 ppm and the volume fraction of CO_2 varies with the natural gas atmosphere. In the table grapes' precooling and cold storage process, the SO_2 gas was released slowly and the level was below 10 ppm. In contrast, the volume fraction of CO_2 was increased gradually. During the table grapes' refrigerated transportation process, the average volume fraction of SO_2 and CO_2 are about 5.86 ppm and 1,202.98 ppm, respectively. After the transportation process, table grapes are stored in the refrigerated warehouse in Tianjin. The volume fraction of SO_2 increases quickly when SO_2 is quickly released by SO_2 generator pads, which reacts with the high relative humidity in the refrigerated warehouse. The average volume fraction of SO_2 and CO_2 are about 58.76 ppm and 9,488.41 ppm, during this time the volume fraction of CO_2 increases quickly due to the respiration of table grapes, then remains stable with the low respiration rate of table grapes at 0℃.

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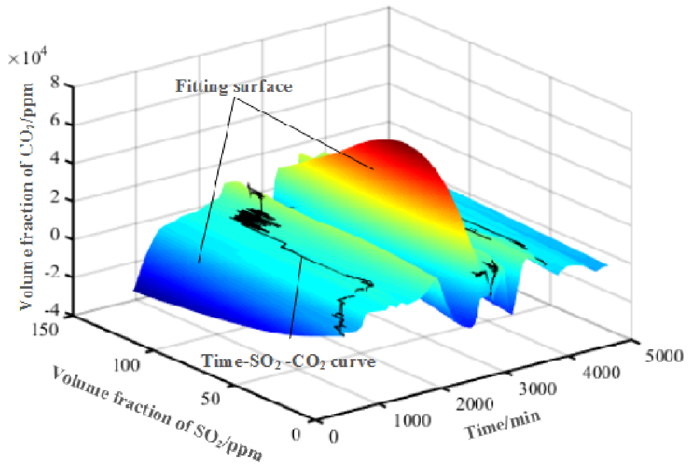

Fig.8. The volume fraction of SO_2 and CO_2 in the table grape cold chain

4.2.2 Table grape chain from Xinjiang to Guangdong

The change of key traceability indicators for table grape chain from Xinjiang to Guangdong is shown in Fig.9. Compare with monitoring data analysis of WGS^2 in the table grape cold chain from Hebei to Tianjin, the changed trend of temperature and SO_2 level are almost the same in the table grape harvesting process at the farm, pre-cooling process, preservation storage process and transportation process. The change of SO_2 level varied quickly in the process of temporary storage for display and sale. The temperature difference and high relative humidity improve the SO_2 gas release rate of SO_2 generator pad or powder in the process of temporary storage for display and sale.

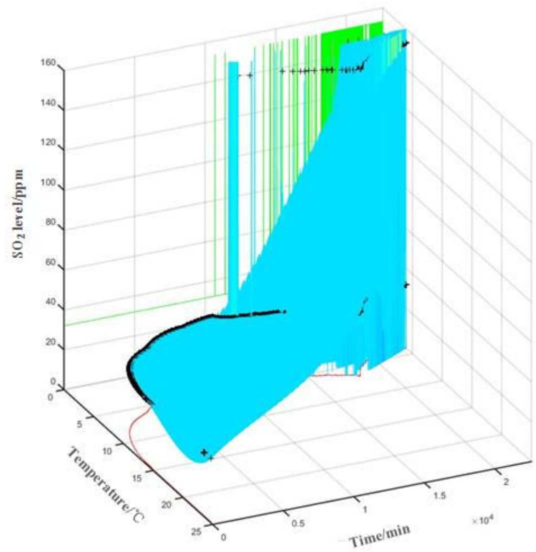

Fig.9 the change of key traceability indicators for table grape chain from Xinjiang to Guangdong

The temperature and relative humidity changes because of the influence of the ambient temperature and the energy released by the life activities of table grape, which changes the CO_2 level by affecting the respiration rate of fruit and SO_2 level by effecting the release rate of SO_2 generator pad or powder. Moreover, the SO_2 level changes the CO_2 level by retarding the respiration rate of table grape. The monitoring data results reflect the atmosphere of table grape cold chain logistics, which could be monitored in real-time via the sensor nodes installed. The results show that WGS^2 system could provide complete and accurate temperature, humidity and gas monitoring information in cold chain, which provide the more effective safety and quality assurance for table grapes in the cold chain.

4.2.3 The comparisons between two cold chain

The comparison between Xinjiang- Guangdong cold chain and Hebei-Tianjin cold chain is shown in Table 3. The distance of two cold chains are 4,300 km and 300 km, respectively. The durations of table grape precooling and grape weight are almost the same for two cold chains. Table grape cold storage duration for Xinjiang- Guangdong cold chain is longer than table grape cold storage duration for Hebei-Tianjin cold chain.

Table 3. The comparisons between two cold chains

Type	Distance	Grape weight	Grape varieties	Grape harvesting duration	Ordinary transportation duration	Table grape precooling duration	Table grape cold storage duration	Transporting the table grapes to retail stores duration	Temporary storage for display and sale
Xinjiang-Guangdong cold chain	4,300 km	10 tons	Seedless grape	Depends on preparation speed of cargo	About 1.5 hours	Approximately 1 day	About 2.5 days	About 5.5 days	Depends on sales
Hebei-Tianjin cold chain	300 km	10 tons	Kyoho grape		About 1 hours	Approximately 1 day	About 9 hours	About 8 hours	

4.3 Shelf-life prediction model considering SO_2

Considering influences of postharvest ripening and constant concentrations of SO_2, the shelf life of table grapes was predicted according the determination quality indicators which including SSC, pH and brown stain and the results of fitted curve. The SSC was determined by a handheld Japanese digital refractometer (Atago PAL-1, Atago Co. Ltd., Tokyo, Japan); the pH value was measured using a Shanghai pH meter (PHS-3C, Jingke Co. Ltd., Shanghai, China); and the brown stain was determined according to a grading of 6 levels: 0 - fresh light green, 1 - green, 2 - dark green, 3 - green to light brown, 4 - brown, 5 - brown to dark grey and dried (Harvey et al, 1988).

The 10 bunches of Kyoho grapes were put into constant temperature incubators with 0 ℃, 10 ℃, 20 ℃, 25 ℃, and the constant SO_2 level with 0 ppm, 10 ppm, 20 ppm. And every bunch of grapes was almost the same weight and size about 1.2 kg. They were picked from a vineyard in Hebei province, China, and were transported on the same day to the laboratory for precooling at 0 ℃. The quality indicators were measured from the samples at same intervals in the same treatment.

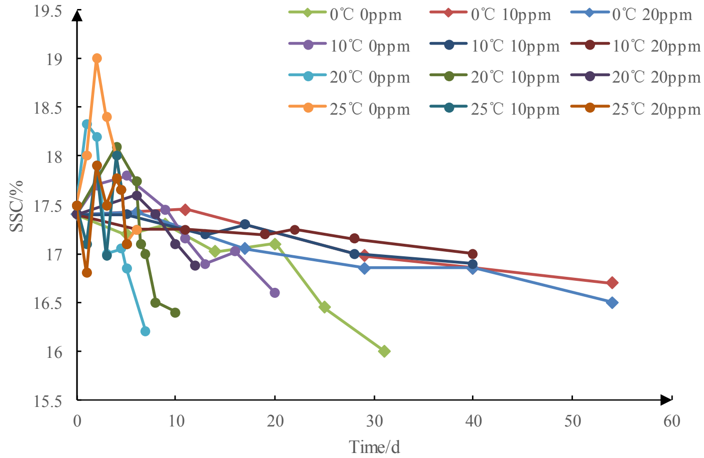

Fig.10. The evolution of SSC at various temperature and constant SO_2 level

The evolution of SSC at various temperature and SO_2 levels is shown in Fig.10. The evolution of SSC in the grapes showed a trend of rising followed by falling at the temperatures higher than 10 ℃, and the peak time at 10 ℃ was obviously latter than the situations at 20 and 25 ℃, while no rising stage for SSC at 0 ℃ was observed. The addition of SO_2 showed effects of inhibition and delay on the accumulating and consuming of SSC in postharvest table grapes, and the effects were enhanced with the increase of SO_2 concentration within a range of 0~20ppm. Then, using the fitted curve to get the model which links the quality indicators to the temperature and SO_2 level. Fig.11. shows the fitted curve of SSC at 0 ℃ and 0 ppm and the fitted coefficients of determination is 0.8219. At last, the shelf life prediction for evolution of pH, brown stain and SSC at various temperature and constant SO_2 level will be get through fitted curve, zero or first-order reaction kinetics model and the Arrhenius equation.

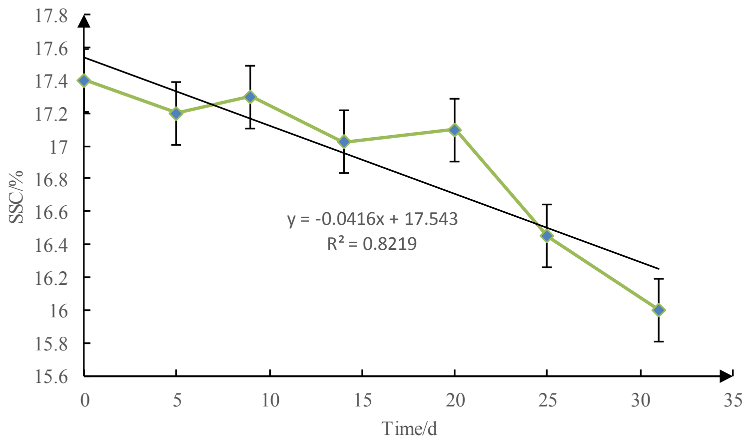

Fig.11. The fitted curve of SSC at 0 ℃ and 0 ppm

Therefore, the shelf life model of table grapes at fluctuant temperature and constant concentrations of SO_2 could be modelled, as shown in Table 4. Table 4 also shows the shelf life prediction model considering SO_2 embedded in the WGS^2 system. The interface of shelf life prediction for table grapes is shown in Fig.12. It consists four parts of indices: the first part displays time; the second part has “check”, “SSC”, “PH” and “brown stain” buttons; the third part displays the monitoring data; the fourth part displays the results of the fitted curve. The evaluation results show that grapes shelf-life prediction model built on the WGS^2 could be used to predict the remaining shelf-life of the grapes during cold chain logistics and provide the effective decision support for the grapes managers in cold chain.

Table 4 Shelf life prediction for table grape

Indexes	SO_2 (ppm)	Shelf life prediction	R^2
brown stain	0	y = -7479.6*x + 24.521	0.9336
	10	y = -9854.6*x + 32.633	0.9759
	20	y = -9037.8*x + 29.846	0.986
SSC	0	y = -9241.2*x + 27.466	0.9531
	10	y=17.4*exp(-0.006*x)	0.8663
	20	y=17.4*exp(-0.006*x)	0.8256
PH	0	y=3.76*exp(-0.006*x)	0.8615
	10	y=3.76*exp(-0.004*x)	0.8663
	20	y=3.76*exp(-0.003*x)	0.8256

x-Celsius degree/℃, y-shelf life/days

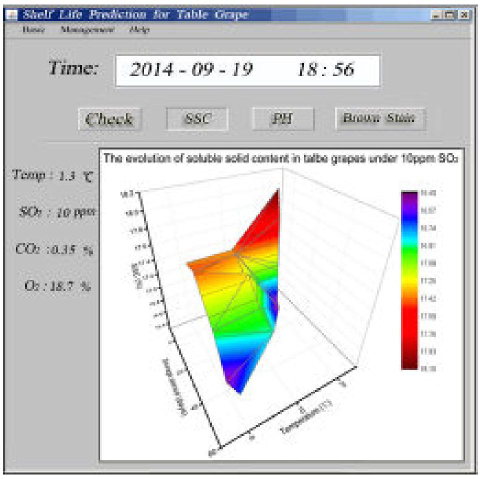

Fig. 12. The interface of shelf life prediction for table grapes.

4.4 Sensor nodes power evaluation

Each sensor node is supplied with a 5V, 30Ah lithium battery. The node power management circuit ensures the sensor node operation is stable until the total voltage drops to 3V (0% battery charge). More power is required to establish the communication link with the low signal link between the SSN and MSN (Xiao et al, 2014). Fig. 13 presents the battery charge status of each sensor node after approximately half month from September 1, 2014 to September 16, 2014. The battery charge status varies from 46% to 60% for all nodes. The batteries of sensor node No.4, No.5 and No.7 were quickly depleted because of the low signal between those nodes and the network MSN, hence more power being required to establish the communication. Based on the results of the experiment, it was predicted that the network can be in normal operation for approximately one month. For table grape chain, it's largely enough for tracing the environmental information by WGS^2 system online.

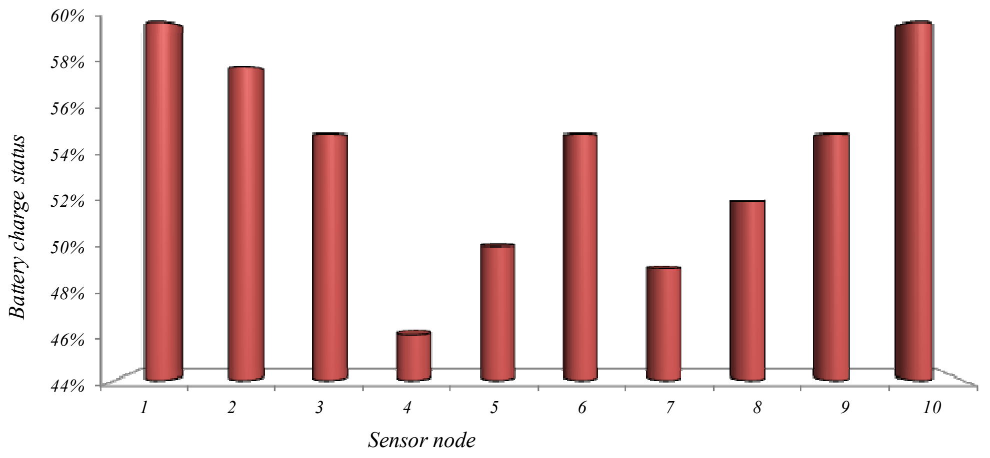

Fig. 13. Battery charge status of the sensor nodes in the network

4.5 System evaluation of the WGS^2

Managers and workers, who have over 3 years of working experience of the table grape production, transportation, cold storage, or sale, who are considered as main stakeholders of the table grape cold chain (as **classified in detail in Fig.2 and page 5**), were invited to take part in a group interview to evaluate the system and discuss the system performance and to feedback on the improvement that the system has enabled to ensure management efficiency of table grape cold chain. It was indicated that the reduced the quality loss and the raised market price of table grapes were resulted from the use of the WGS^2 system's real-time monitoring and shelf life prediction. Table 5 shows the efficiency and performance analysis for the WGS^2 implementation. As can be seen, the implementation of WGS^2 has improved the cold chain gas environment monitoring greatly, which improves the traceability of the table grapes and enables better table grape cold chain management.

Table 5. Cold chain monitoring performance analysis for WGS^2 implementation

System performance indicators	Cold chain logistics temperature and humidity monitoring	Cold chain logistics SO_2 gas monitoring	Cold chain logistics CO_2 gas monitoring	Cold chain logistics O_2 gas monitoring	Cold chain shelf life prediction	Data signal analysis method	Quality loss	Market price (RMB)
Traditional work	Recorders or radio frequency identification technology, high cost and offline	Null	Null	Null	Only based on temperature	Null	25%~30%	<8yuan/kg
Previous work in our team	Range:-40 to -124℃ Accuracy:±0.4℃	Range:0-20ppm Accuracy:±5%FS Power:0.5w	Null	Null	Only based on temperature	Null	<19%	<10yuan/kg
WGS^2 system	Range:-40 to -80℃ Accuracy:±0.3℃	Range:0-150ppm Accuracy:±2%FS Power<0.25w	Real-time	Real-time	Based on temperature and SO_2 gas	Embedded	<10%	>16yuan/kg
Advantage	Better accuracy of temperature monitoring and traceability	Better accuracy and power of the SO_2 monitoring and traceability	Capability of CO_2 monitoring and traceability	Capability of O_2 monitoring and traceability	Capable of capturing and defining the link between grape quality and SO_2 gas	Improving traceability and transparency of table grape cold chain	Reduce the quality loss for table grape cold chain	heightening benefit for table grape cold chain

Table 6. Cased by SO_2 sensors in WGS^2 system performance analyzed in detail

Class	Industrial	Cold chain (online)	E-nose/E-tongue
Scale range	>2000 ppm	<100ppm	small
Accuracy	±20ppm	±1ppm	low
Power supply	High Supporting	Low Self-supporting	High Supporting
Signal processing	Data & early warning	Quality coupling	Quality coupling
Online	Online	Online accumulative	Offline/fast

Table 6 lists the cased by SO_2 gas sensors in WGS^2 system performance analyzed in detail. Scale range of industrial SO_2 gas sensor is normally above 2000 ppm and the accuracy is above ±20ppm; Industrial sensors have fixed power supply. On the other hand, E-nose or E-tongue is widely used to detect specifications of mixed gas offline and roughly calculate the amount of gas. In comparison, table grape cold chain sensors in WGS^2 have high accuracy, small size, capable of online and low power consumption which be self-supported by portable power supply from field observation.

5. Conclusions

This paper presents a novel system of the WGS^2, which is developed and implemented in two table grape cold chains from Hebei to Tianjin, China and Xinjiang to Guangdong, China. This WGS^2 technology enables a real-time sensor data acquisition, offers high accuracy and efficiency without the need of complicated infrastructure. The WGS^2 system can help the cold chain managers to carry out real-time monitoring of the key traceability indicators, so that to control the safety and quality of table grapes cold chain more effectively.

The system test and evaluation show that WGS^2 can monitor the state of the cold chain by acquiring and transmitting the real-time temperature, humidity, SO_2, CO_2, and O_2 in the cold chain, helping managers and workers monitor the cold chain in a timely manner and resolve any problems that may cause unexpected quality loss. The grape shelf-life prediction results indicate that the grapes shelf-life prediction model built in the WGS^2 can be used to predict the SSC, pH and brown stain change and the remaining shelf-life of table grapes cold chain.

The WGS^2 can transmit the sensed gas data to the remote monitoring centre in real-time via the wireless network and the GPRS remote transmission module from the spot and reflect the environmental information accurately. Moreover, the wireless network has a relatively reliable signal in the cold chain scenario and can display reliable transmission of the sensor data in the cold chain.

The network was estimated to be able to operate successfully for approximately one month with sufficient the battery charge status of each sensor node. The signal quality of GPRS in the container may be influenced by the environmental changes, such as temperature or humidity changes, and windy or rainy weather. Moreover, the signal quality of WSN in the container may be affected by the materials and thickness of the container. Therefore, the on-site resistance and stability of the WGS^2 can be improved. Moreover, it is necessary to integrate low energy consumption sensors into the SSN to meet the demands of actual application.

Although the WGS^2 is developed to monitor the table grape cold chain, the system architecture and the system models can be exploited by future researchers or practitioners to develop monitoring systems to for much wider cold chain monitoring tasks.

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